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A CENSUS OF RINGS IN THE GULF STREAM SYSTEM.(U)

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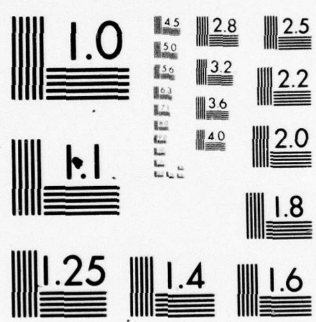

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A CENSUS OF RINGS IN

THE GULF STREAM SYSTEM

by

R.E. Cheney

U.S. NAVAL OCEANOGRAPHIC OFFICE

WASHINGTON, D.C. 20373

NAVOCEANO Technical Note 3700-44-76

January 1976

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (*When Data Entered*)

14 N00-TN-3700-44-76

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
Technical Note 3700-44-76

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (*and Subtitle*)
6 A Census of Rings in the Gulf Stream System.

5. TYPE OF REPORT & PERIOD COVERED
9 Technical note,

6. ~~PERFORMING ORG. REPORT~~ NUMBER

7. AUTHOR(s)
10 Robert ~~R.~~ E./Cheney

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
U.S. Naval Oceanographic Office
Washington, D.C. 20373

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

11. CONTROLLING OFFICE NAME AND ADDRESS
U.S. Naval Oceanographic Office
Washington, D.C. 20373

12. ~~REPORT DATE~~
11 Jan[redacted]76

13. ~~NUMBER OF PAGES~~
26

14. MONITORING AGENCY NAME & ADDRESS (*if different from Controlling Office*)

15. SECURITY ~~CLASS. (of this report)~~
12 28p.
UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (*of this Report*)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (*of the abstract entered in Block 20, if different from Report*)

18. SUPPLEMENTARY NOTES

Environmental data collected for Eddy SUBEX 75.

19. KEY WORDS (*Continue on reverse side if necessary and identify by block number*)

Oceanography	Mixed Layer Depths
Currents	Water Temperature
Atlantic Ocean	Salinity
Eddies	

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

Ten cyclonic and three anticyclonic Gulf Stream rings were identified using 700 bathythermographs and STD's between 22 June and 9 July 1975. Two cyclonic rings were tracked for 7 and 11 months, and an anticyclonic ring was tracked for 10 months. An average of five cyclonic and anticyclonic rings form each year with lives of two and one year respectively.

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ABSTRACT

In order to provide environmental data for EDDY SUBEX 75, an acoustic experiment carried out by the U.S. Naval Oceanographic Office, a ship survey was conducted between 22 June and 9 July 1975. Thermal features in the Sargasso Sea and the Gulf Stream system northwest of Bermuda were mapped using 760 m XBT's and deep STD stations. Four cyclonic Gulf Stream rings and one anticyclonic ring were found. Repeated observations of two of the cyclonic rings over periods of seven and eleven months indicates a net southwestward drift for both rings of about 3 km day^{-1}. The anticyclonic ring, observed for 10 months, moved southwest at 5 km day^{-1}. It is one of the most pronounced ever observed with the main thermocline at the center nearly 500 m deeper than the thermocline in the surrounding Slope Water. The largest of the cyclonic rings is believed to be an "extension ring", perhaps formed as far east as 55°W by the downstream extension of the Gulf Stream. T-S properties at the center of this ring show the influence of Mediterranean Water and distinguish it from other cyclonic rings in the western Sargasso Sea. Mixed layer depths were less than 50 m throughout the study area, typical for early summer. Passage of a tropical storm through the region caused an increase in the layer depth of about 20 m.

When these observations are combined with those of two Woods Hole Oceanographic Institution scientists it is possible to locate thirteen different Gulf Stream rings: ten cyclonic and three anticyclonic. These are the largest number of distinctly different rings ever observed in a near-synoptic survey of this type. This number is consistent with previous estimates of five cyclonic rings forming per year, each with a lifetime of two years. Since anticyclonic rings are known to have shorter lifetimes (less than one year) an equal number of this type may also form during a year.

I. INTRODUCTION

A search for Gulf Stream rings was carried out in the northwestern Sargasso Sea and adjacent Slope Water during the period 22 June to 9 July 1975. This survey provided environmental data for EDDY SUBEX 75, an acoustic experiment conducted by the Naval Oceanographic Office in late June. The thermal structure of the region was mapped primarily using T-7 SXBT's (shipboard expendable bathythermographs) which could be read to a depth of approximately 850 m. Deep temperatures and salinities in areas of particular interest were obtained with STD (salinity temperature depth) casts. Additional data were provided by AXBT's (airborne expendable bathythermographs) and continuous temperature measurement by a submarine.

These data cover an area of about 500,000 km^2 in the northwestern Atlantic. Their distribution, together with satellite infrared imagery obtained during this period, assures that all rings within this area were located.

II. RING DISTRIBUTION

The cruise track of USNS LYNCH is superimposed on depth contours of the 15°C isothermal surface throughout the study area in Fig. 1. The Gulf Stream's North Wall (15°C at 200 m) was tracked between 75°W and 68°W in order to determine the extent of meandering. While searching for rings SXBT's were dropped at intervals of about 18 km. A total of five rings were found during the survey; four cyclonic (cold) rings south

of the Gulf Stream and one anticyclonic (warm) ring north of the Stream (Fig. 1).

Four of the rings had known histories of 3 to 7 months, as indicated in Fig. 2 and Table 1; tracking of three of these has continued through October and November 1975. The cold rings have exhibited general southwestward migrations at speeds of about 3 km day^{-1}. The warm ring has moved southwest at 5 km day^{-1}. A fifth ring, which had not been observed previously, was located just off Cape Hatteras but was only partially surveyed during this cruise.

Table 1
RING TRACKING OBSERVATIONS

	DATE	POSITION	TYPE OF DATA
Code ring 1	24 April 75	36.0°N, 64.5°W	NOAA satellite
	*28 June	36.7°N, 66.5°W	USNS LYNCH XBT
Code ring 2	24 March 75	36.5°N, 66.2°W	NOAA satellite
	10 April	36.5°N, 66.7°W	aircraft XBT
	24 April	36.0°N, 66.8°W	NOAA satellite
	12 May	35.7°N, 67.2°W	NOAA satellite
	21 May	35.7°N, 67.7°W	aircraft XBT
	9 June	35.9°N, 68.3°W	R/V TRIDENT XBT
	17 June	35.5°N, 68.5°W	aircraft XBT
	*25 June	35.4°N, 68.6°W	USNS LYNCH XBT
	8 August	34.6°N, 69.9°W	R/V CHAIN XBT
	6 October	34.5°N, 70.4°W	R/V EASTWARD XBT
	14 October	34.8°N, 70.8°W	aircraft XBT
Cold ring 3	November 74	36.7°N, 58.5°W	R/V KNORR XBT
	24 January 75	34.5°N, 59.7°W	R/V CHAIN XBT
	March	34.0°N, 62.5°W	R/V KNORR XBT
	May	33.5°N, 64.0°W	R/V KNORR XBT
	17 June	34.0°N, 65.0°W	aircraft XBT
	* 5 July	34.1°N, 64.4°W	USNS LYNCH XBT
	16 October	33.0°N, 67.5°W	aircraft XBT

	DATE	POSITION	TYPE OF DATA
Warm ring	15 January 75	40.5°N, 63.0°W	NOAA 4 satellite
	17 February	41.0°N, 64.0°W	NOAA 4 satellite
	10 March	40.0°N, 65.5°W	NOAA 4 satellite
	3 April	39.5°N, 67.2°W	NOAA 4 satellite
	11 May	39.5°N, 69.0°W	NOAA 4 satellite
	10 June	39.0°N, 70.3°W	R/V TRIDENT XBT
	*29 June	39.0°N, 71.0°W	USNS LYNCH XBT
	3 August	38.5°N, 72.0°W	NOAA 4 satellite
	3 September	38.0°N, 72.7°W	NOAA 4 satellite
	30 September	37.0°N, 74.0°W	NOAA 4 satellite
	** 5 November	36.5°N, 74.0°W	NOAA 4 satellite

* Data presented in this report.

**Ring coalesced with Gulf Stream.

III. DEEP THERMAL STRUCTURE

a. Gulf Stream and Sargasso Sea

Figure 3 is a temperature section from off Cape Henry, Virginia through the Gulf Stream and Sargasso Sea to Bermuda. Although the section does not pass through the rings, the influence of cold rings 2 and 3 in the far field is apparent; the main thermocline is uplifted slightly 500 km and 900 km from the start of the section. The seasonal thermocline indicated by the 21°C and 23°C isotherms is not effected, however.

b. Cold Ring 1

The size of Gulf Stream rings can be presented by plotting depth contours of their 15°C isothermal surface. At the center of a cold ring the main thermocline may be 600 m shallower than the thermocline in the surrounding Sargasso Sea. The 15°C isotherm is chosen to describe this elevation since it is in the main thermocline (7°C to 17°C) yet it is sufficiently shallow to be penetrated with standard T-7 SXBT probes. A plot of 15°C depth

provides a measure of the ring's horizontal extent as well as the height of the "dome" of cold water formed by the raised thermocline at the center.

Three distinctly different sizes of cyclonic rings were observed. Cold ring 1 (Figs. 4a and 4b) is the smallest of the rings and presumably, by comparison of the temperature sections shown later, also the oldest. Nevertheless, cyclonic circulation as measured by ship drift was strong with maximum surface currents of 2.4 knots (123 cm sec^{-1}). Its known history goes back to 24 April 1975 when it was first observed by satellite 200 km southeast of its 27 June position. It is unusual for such an old-looking ring to be found in an area which is ordinarily occupied by more newly formed rings. The possibility exists, therefore, that ring 1 is a relatively new feature whose structure has been altered in some way since formation (splitting into two parts of interacting with the Gulf Stream, for example).

c. Cold ring 2

Next largest is size is cold ring 2 (Figs. 5a and 5b) which had been tracked by satellite, aircraft and ship for three months prior to the June survey. Its movement during this period was toward the southwest at 2.7 km day^{-1}. Temperature sections show ring 2 to be considerably colder and to have stronger temperature gradients than ring 1; this is reflected in the surface currents which reached maximum speeds of 3.4 knots (175 cm sec^{-1}).

Its structure is characteristic of a relatively new, average sized cyclonic Gulf Stream ring. STD's through the center show the ring's structure to extend as deep as 3000 m (maximum depth sampled).

d. Cold ring 3

Cold ring 3, surveyed during 4 to 6 July (Figs. 6a and 6b), had been followed sporadically since November 1974 by Woods Hole and NAVOCEANO researchers (Cheney and Richardson, 1975a). During this period its net movement was to the southwest at 2.8 km day^{-1}. Despite its age of at least seven months, temperatures at the center are still quite cold, although the interior cold dome is relatively narrow. The ring's thermal structure extends to about 2500 m but begins to disappear below this depth. Its unusually large overall size places it in a class of rings known as "big babies" or Gulf Stream "extension rings" (McCartney, 1975). It is thought that these features are formed by the downstream extension of the Gulf Stream, perhaps as far east as 50°W, and may originally contain a core slightly different than Slope Water.

Evidence of the nature of this difference is provided by T-S diagrams from STD stations within the extension ring. Figure 7 compares the standard T-S curve for the North American Basin (Wright and Worthington, 1970) with that of an STD cast at the center of cold ring 3. The two curves are identical except that the water between 5°C and 7°C in ring 3 is about 0.070°/₀₀ more saline. This is contrasted with the T-S curve from the center of cold ring 2 which follows the standard

curve more closely in this temperature range. The third T-S curve in Fig. 7 represents Mediterranean Water after it enters the Atlantic. This highly saline water flows westward through the Straits of Gibraltar to form the Upper Deep Water of the Atlantic (Neumann and Pierson, 1966) which can be detected out to 60°W (Fig. 8). Maximum salinity of the Upper Deep Water at this longitude is about 35.1 ‰ which occurs at a depth of 1000 to 1250 m; this is the same salinity and depth at which the anomaly in ring 3 occurs. It thus appears that because extension rings are formed in the east they contain traces of Mediterranean Water in the deep layers. This anomalous T-S characteristic can be used to differentiate extension rings from other cyclonic rings in the Western Sargasso Sea.

e. Warm ring

The anticyclonic ring, surveyed on 29 June, (Figs. 9a and 9b) is one of the most pronounced warm rings ever observed. The ring's movement, monitored since 15 January by satellite imagery and aircraft XBT's, had been to the southwest counter to the Gulf Stream at a rate of 5.1 km day^{-1}. Despite the ring's age the main thermocline is depressed nearly 500 m at the ring center. Clockwise surface currents as fast as 2.7 knots (139 cm sec^{-1}) were measured.

IV. MIXED LAYER DEPTH

In March it is not uncommon to find mixed layer depths of 200 m in Slope Water and 400 m in the Sargasso Sea as a result of winter cooling. In the Gulf Stream, where water in the surface

layers is constantly being replaced by warm water from lower latitudes, a deep mixed layer does not have time to develop and the layer depth is relatively shallow (100 m or less). As spring warming begins these isothermal conditions rapidly disappear, and a thin mixed layer of warm water forms above the seasonal thermocline. This layer increases in thickness during summer.

The survey presented here was conducted in early summer after the formation of the warm mixed layer. Averaged mixed layer depths for the various water masses and Gulf Stream rings sampled are given in Table 2. Because of Tropical Storm Amy, which passed directly through the survey area between 28 June and 2 July (Fig. 10), the observations are separated into pre-storm and post-storm categories. For those regions that were sampled both before and after the storm a marked increase in layer depth was noted. Layer depth in Slope Water increased from 0 to 20 m, in the Gulf Stream from 40 to 65 m, and in the warm ring from 5 to 20 m.

Table 2
MIXED LAYER DEPTHS

	Depth (m) before storm	Depth (m) during or after storm
Slope Water	0	20
Gulf Stream	40	65
Sargasso Sea	-	45
Warm ring	5	20
Cold ring 1	0	-
Cold ring 2	30	-
Cold ring 3	-	40

V. DISCUSSION

It has been estimated that approximately 5 cold rings and 5 warm rings form each year (Fuglister, 1972). Several time series of ring observations indicate typical lifetimes of slightly less than one year for warm rings (Gotthardt, 1974, Potocsky, 1973, Thompson and Gotthardt, 1971) and two to three years for cold rings (Cheney and Richardson, 1975b, Richardson, Cheney, and Gemmill, 1975). This implies that at any one time there might be 3 to 4 warm rings and 10 to 15 cold rings present in the western North Atlantic.

In an attempt to test the accuracy of these estimates the data presented in this report were combined with NOAA-4 satellite infrared imagery and observations of two Woods Hole investigators during the same time frame in order to take a census of all existing rings. Ship observations include those of Worthington aboard R/V KNORR (7 March to 16 April, 1975) and Richardson aboard R/V TRIDENT (24 May to 11 June, 1975). These data reveal the presence of 13 different Gulf Stream rings: 10 cold and 3 warm (Fig. 11). Cold rings A-F are depicted by contours of 15°C at 600 m and warm ring H is delineated by 15°C at 100 m. Boundaries for rings I, J, and G are approximations from satellite infrared imagery. The dashed boundary of ring C indicates insufficient XBT data to accurately determine size and shape. Rings K, L, and M were observed during March and April and are discussed by McCartney (1975). The Gulf Stream's North Wall (15°C at 200m) was tracked during 22 to 23 June between 75°W and 68°W. The offshore edge of the Gulf Stream is approximated

by 15°C at 600 m. Elsewhere, dashed lines indicate the Stream's path as revealed by satellite photographs in late June.

Dates corresponding to the ring positions shown in Fig. 11 are given in Table 3. Six of the rings had been tracked for periods from two to eleven months at the time of the June survey. The remaining four rings were observed for the first time, although some of these are clearly old.

These are the largest number of distinctly different Gulf Stream rings ever observed in a near-synoptic survey of this type. Additional rings may be located south of the surveyed region. The number of rings is consistent with previous estimates of five forming to each side of the Gulf Stream during a year.

Table 3
OBSERVATIONS OF THIRTEEN DIFFERENT RINGS

Ring	Date (1975)	Platform*	Observations	Earliest Observation
A	26 May	TRIDENT	55 XBT, 2 CTD-O_2	none
B	1 June	TRIDENT	43 XBT, 3 CTD-O_2	20 June 1974
C	2 July	LYNCH	7 XBT	none
D	7-8 June	TRIDENT	52 XBT, 2 CTD	24 March 1975
	24-27 June	LYNCH	60 XBT, 9 STD	
E	28 June	LYNCH	20 XBT	24 April 1975
F	4-6 July	LYNCH	35 XBT, 5 STD	November 1974
G	22 June	NOAA-4	Infra-red imagery	none
H	10 June	TRIDENT	8 XBT	
	29 June	LYNCH	40 XBT	23 Feb. 1975
I	24 June	NOAA-4	Infra-red imagery	9 March 1975
K	7 March			
L	to	KNORR	(McCartney, 1975)	
M	16 April			

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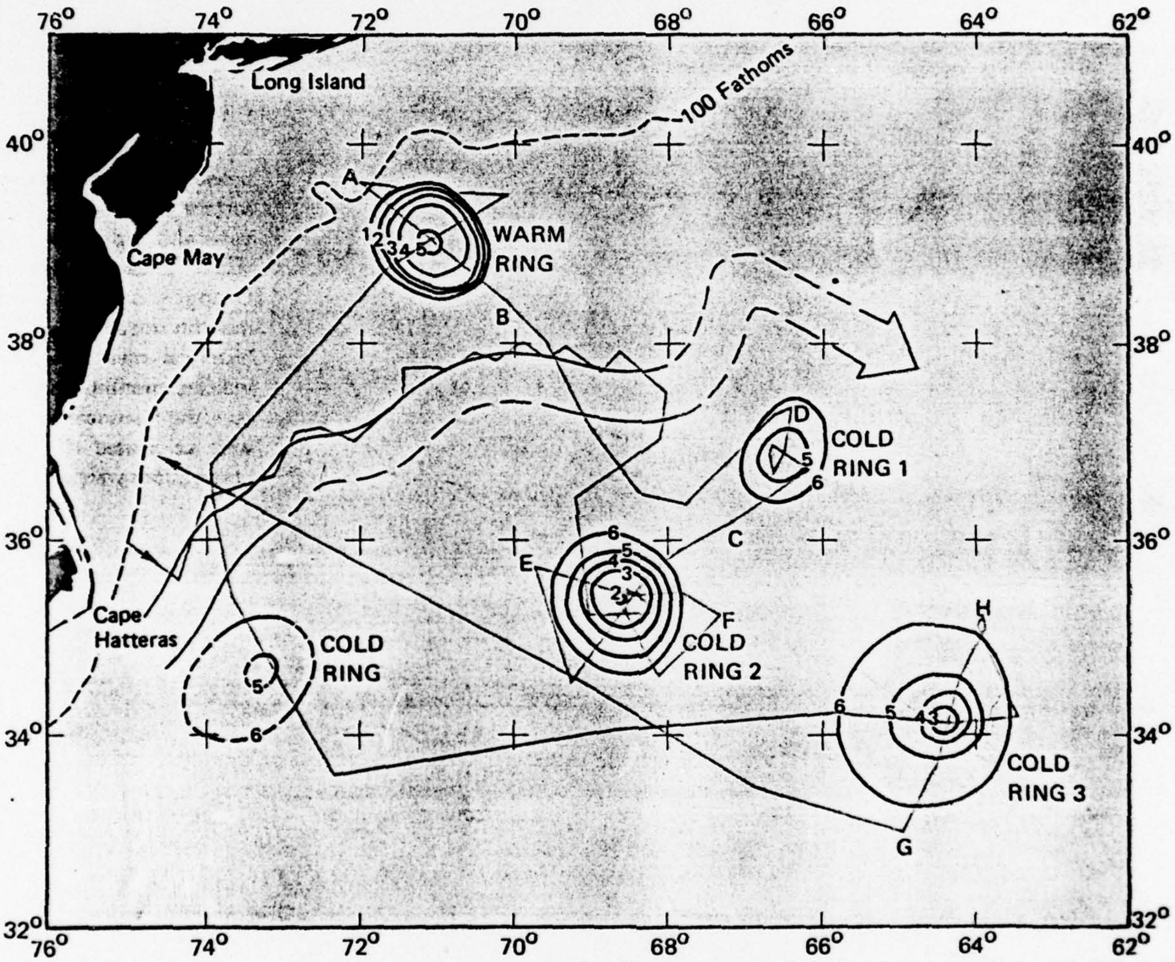


Fig. 1 - Depth (10^2 m) of the 15°C isothermal surface, 22 June to 9 July 1975. Gulf Stream is depicted by 15°C at 200 m (north wall) and 600 m; elsewhere dashed contours represent satellite imagery. Track of USNS LYNCH is superimposed.

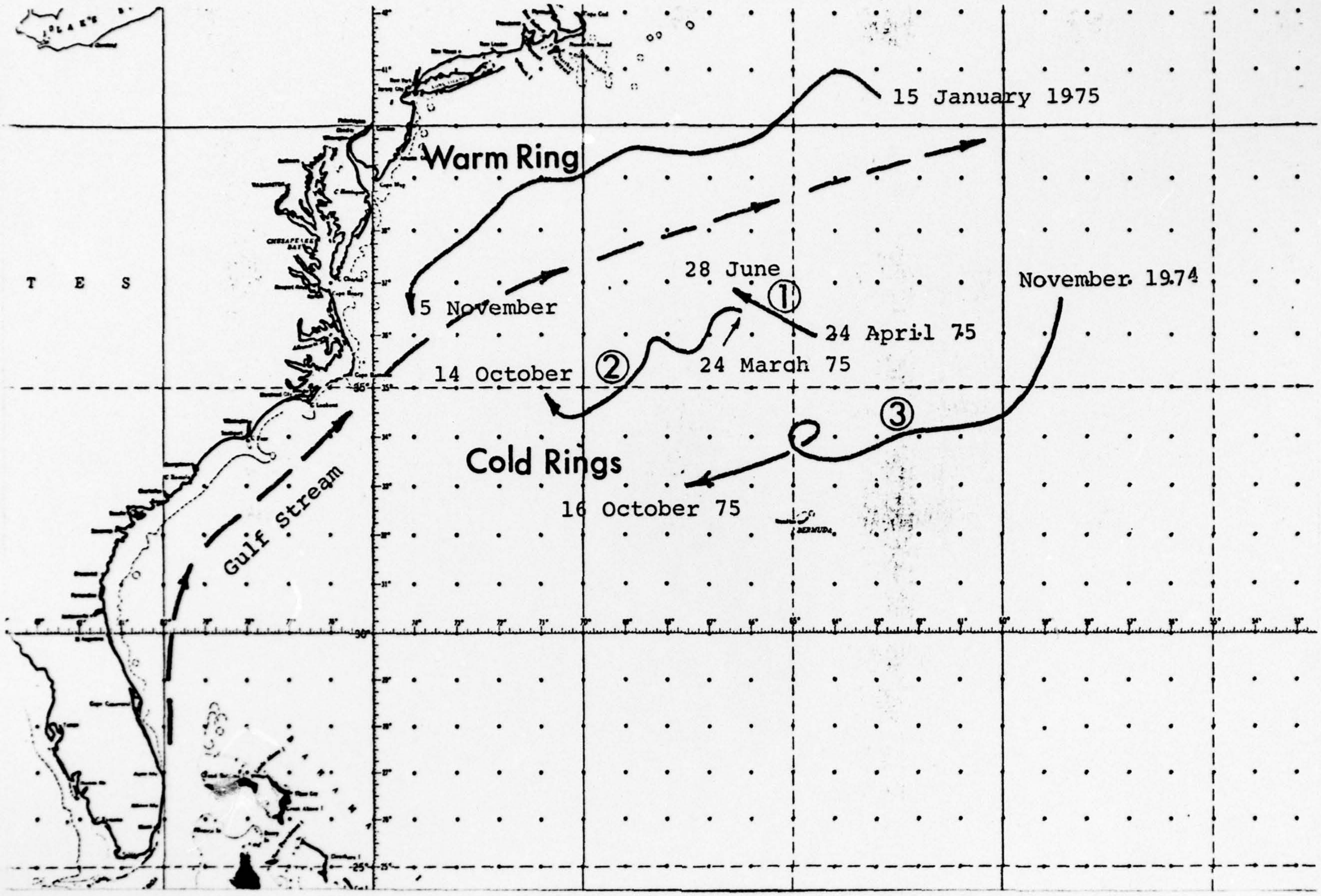


Fig. 2 - Observed movement of cold rings 1, 2, and 3 and warm ring. Dashed line is historical mean Gulf Stream. The warm ring coalesced with the Stream in November. Ring 1 has not been observed since 28 June. Tracking of rings 2 and 3 is continuing.

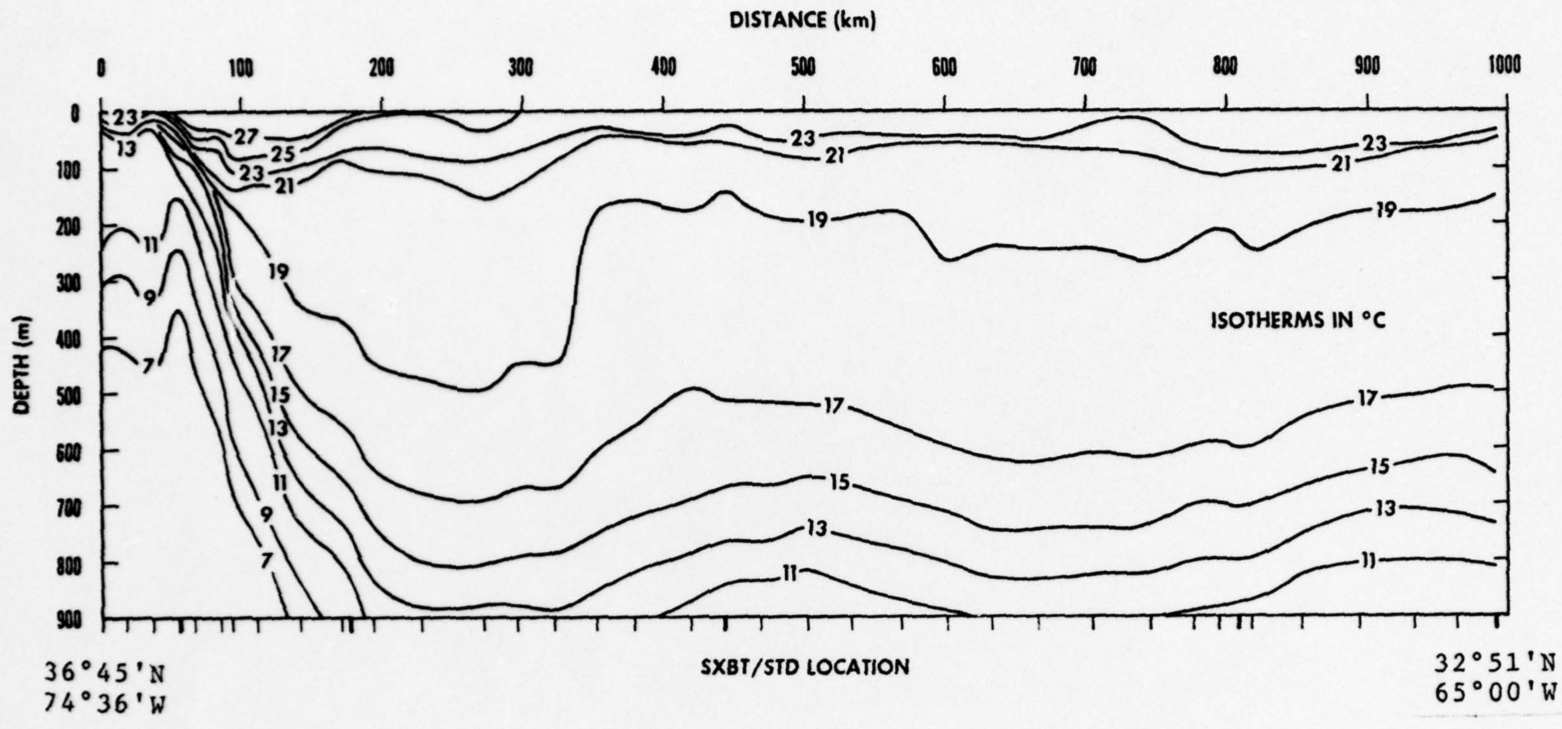


Fig. 3 - Temperature section from off Cape Henry, Virginia through Slope, Gulf Stream, and Sargasso Sea Water to Bermuda. Slight uplifting of main thermocline at 500 and 900 km is due to rings 2 and 3, both centered about 100 km north of the section.

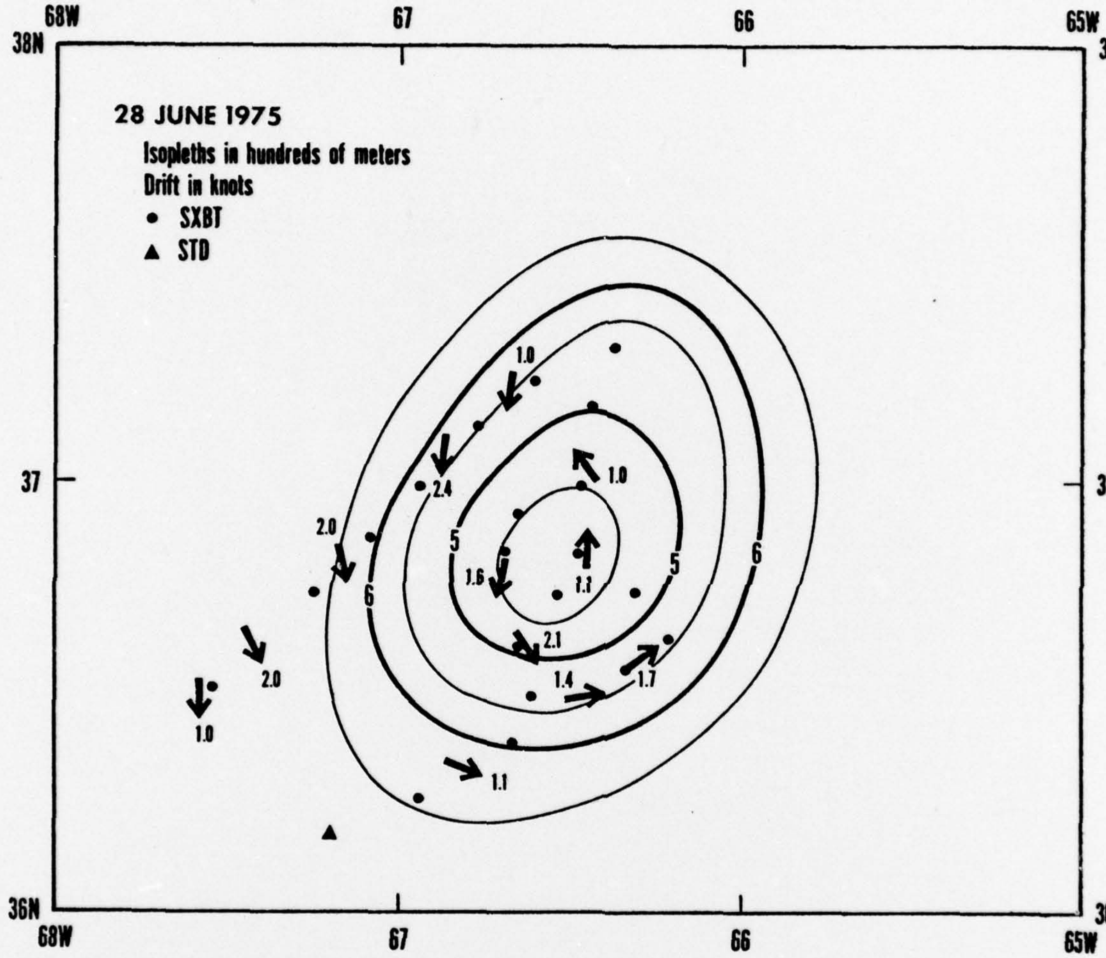


Fig. 4a - 15°C depth (10^2 m) in cold ring 1, 28 June 1975. SXBT's are shown as dots. Cyclonic surface currents as measured by ship drift are indicated in knots.

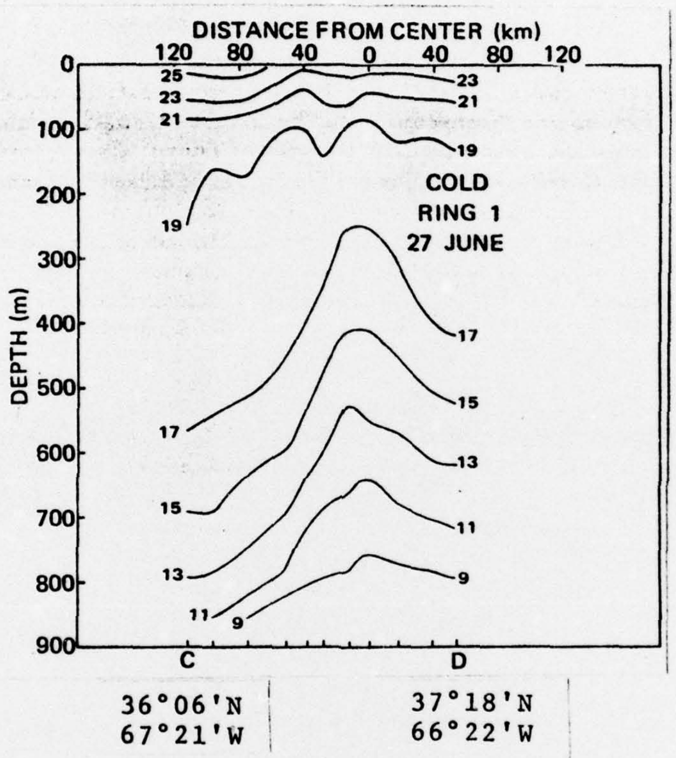


Fig. 4b - Temperature section through ring 1. SXBT positions are shown along bottom.

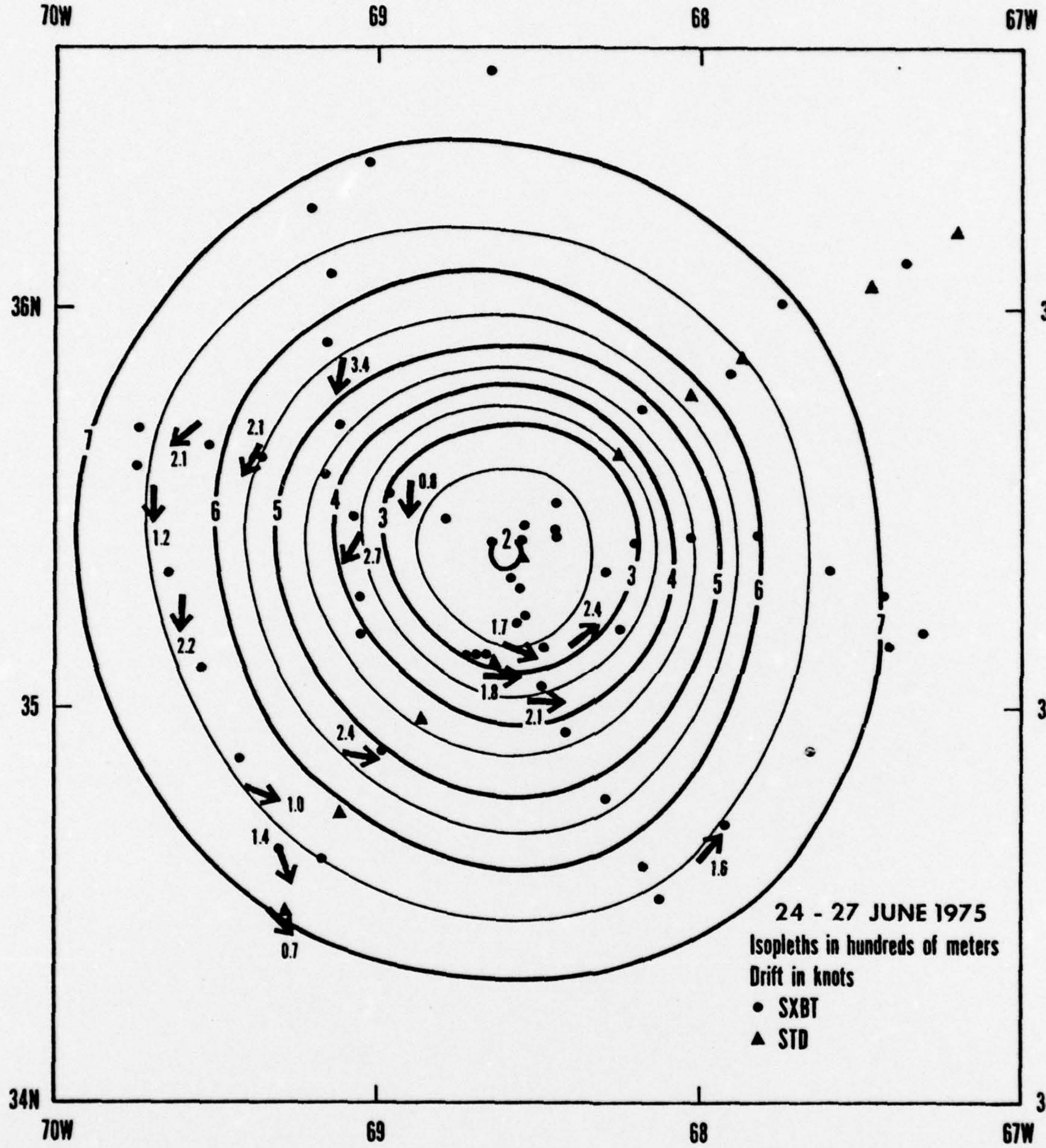


Fig. 5a - 15°C depth (10^2 m) in cold ring 2, 24 to 27 June 1975. Solid triangles indicate STD stations. Dots represent SXBT's. Cyclonic surface currents as measured by ship drift are indicated in knots.

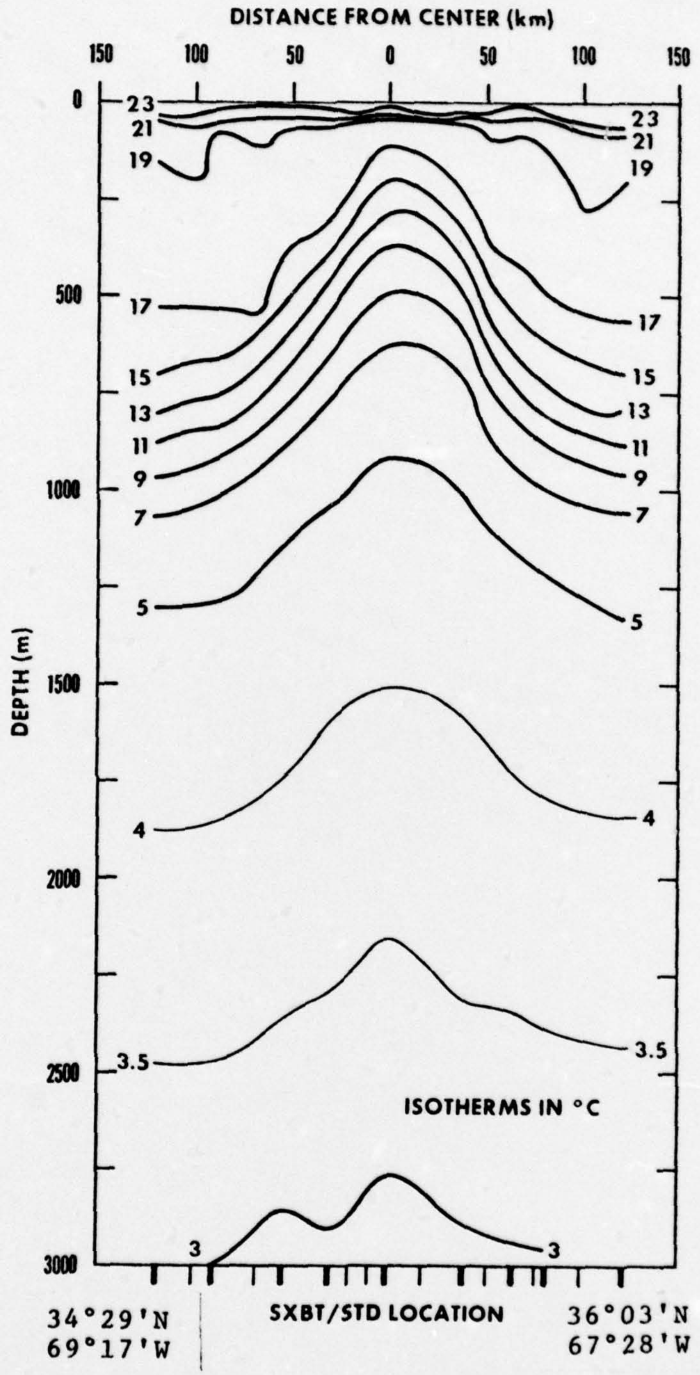


Fig. 5b - Deep temperature section through cold ring 2, 26 to 27 June 1975. STD stations are indicated by heavy lines at bottom, SXBT's by thin lines.

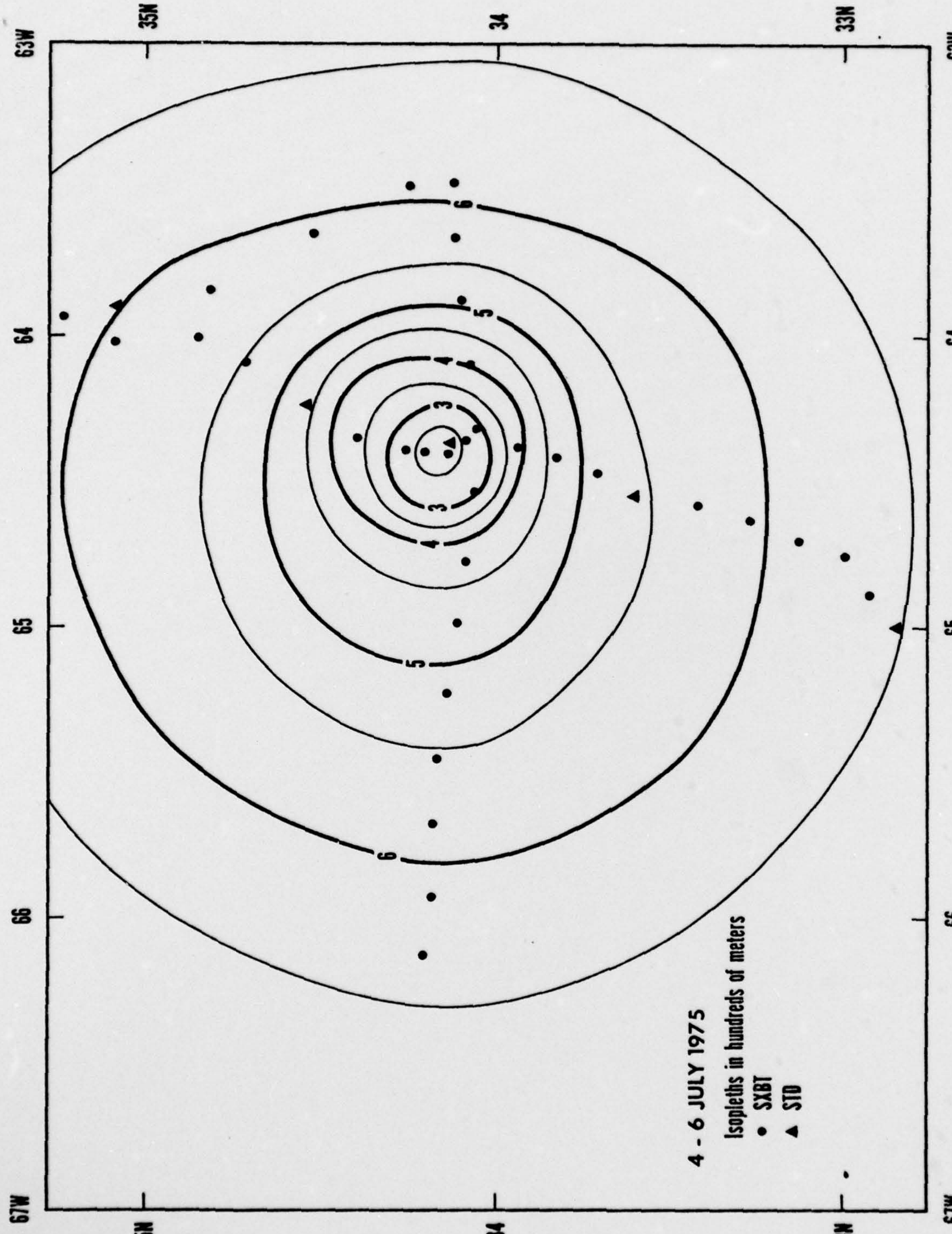


Fig. 6a - 15°C depth (10^2 m) in cold ring 3, 4 to 6 July 1975. STD and SXBT positions are shown as solid triangles and dots.

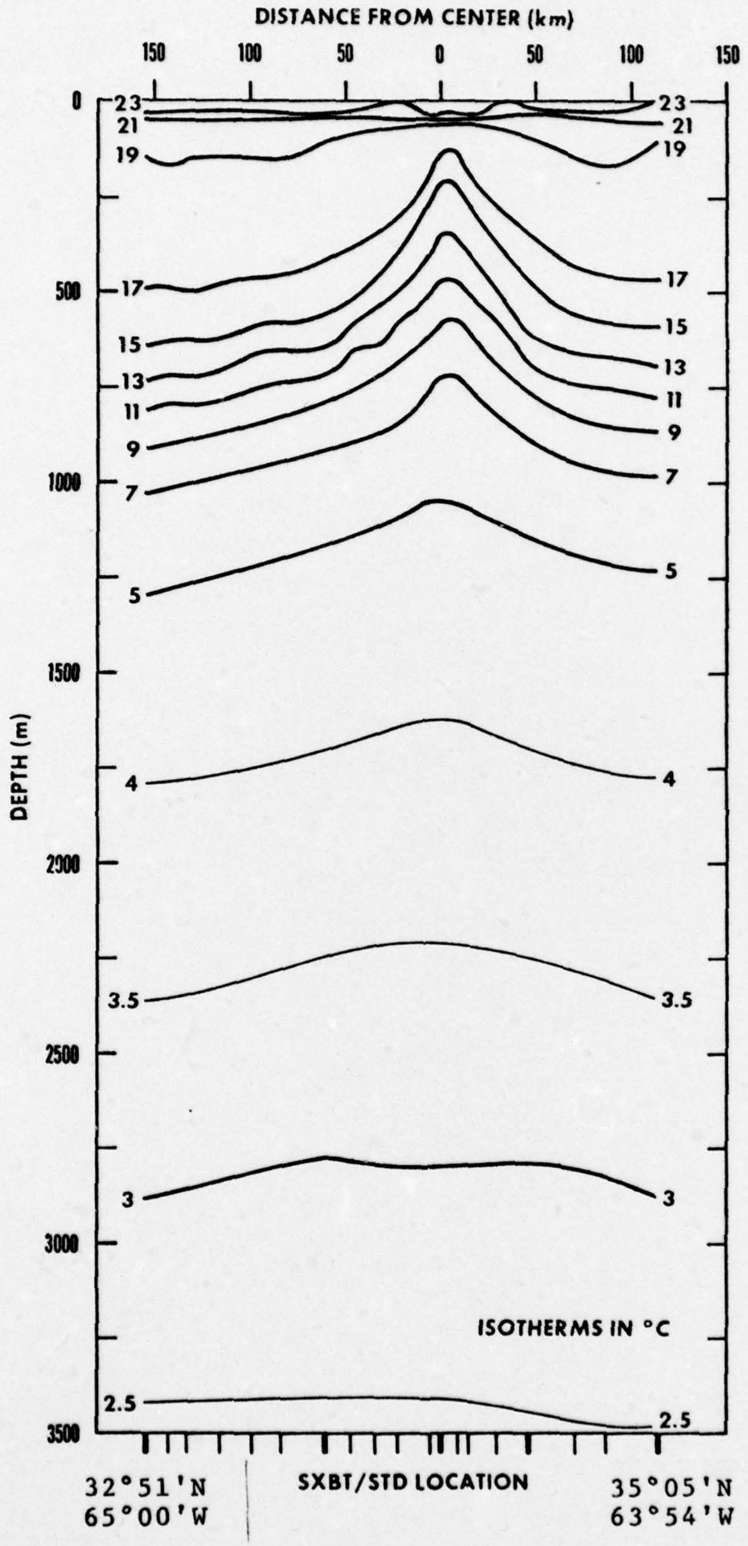


Fig. 6b - Deep temperature section thro8gh cold ring 3, 5 to 6 July 1975. STD stations are indicated by heavy lines at bottom SXBT's by thin lines.

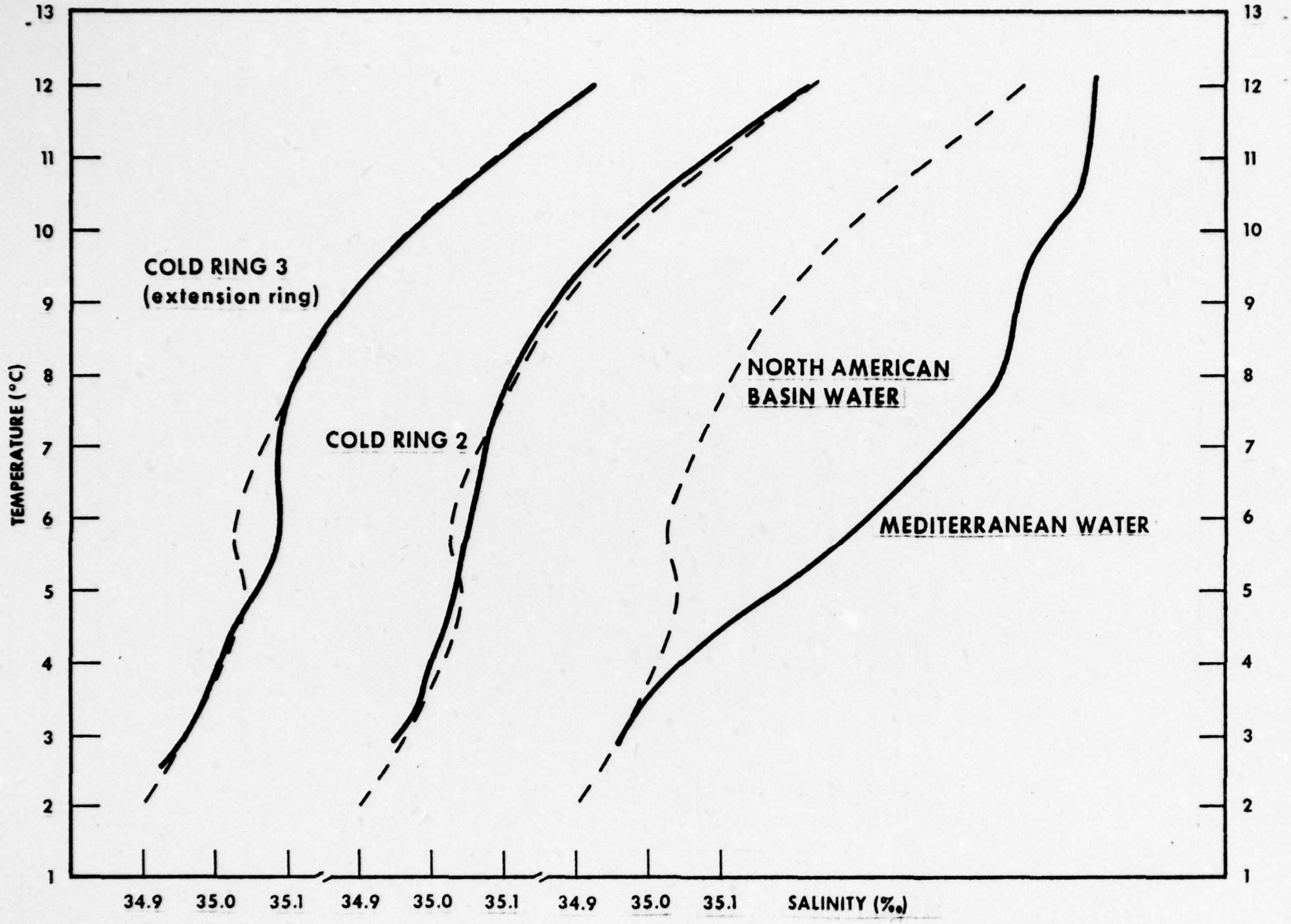


Fig. 7 - T-S diagrams from the center of cold rings 2 and 3 as compared to the standard curve for the North American Basin (dashed curve). Typical Mediterranean Water is shown at right. The salinity anomaly in ring 3 between 5°C and 7°C is believed to be due to the influence of Mediterranean Water in the formation area.

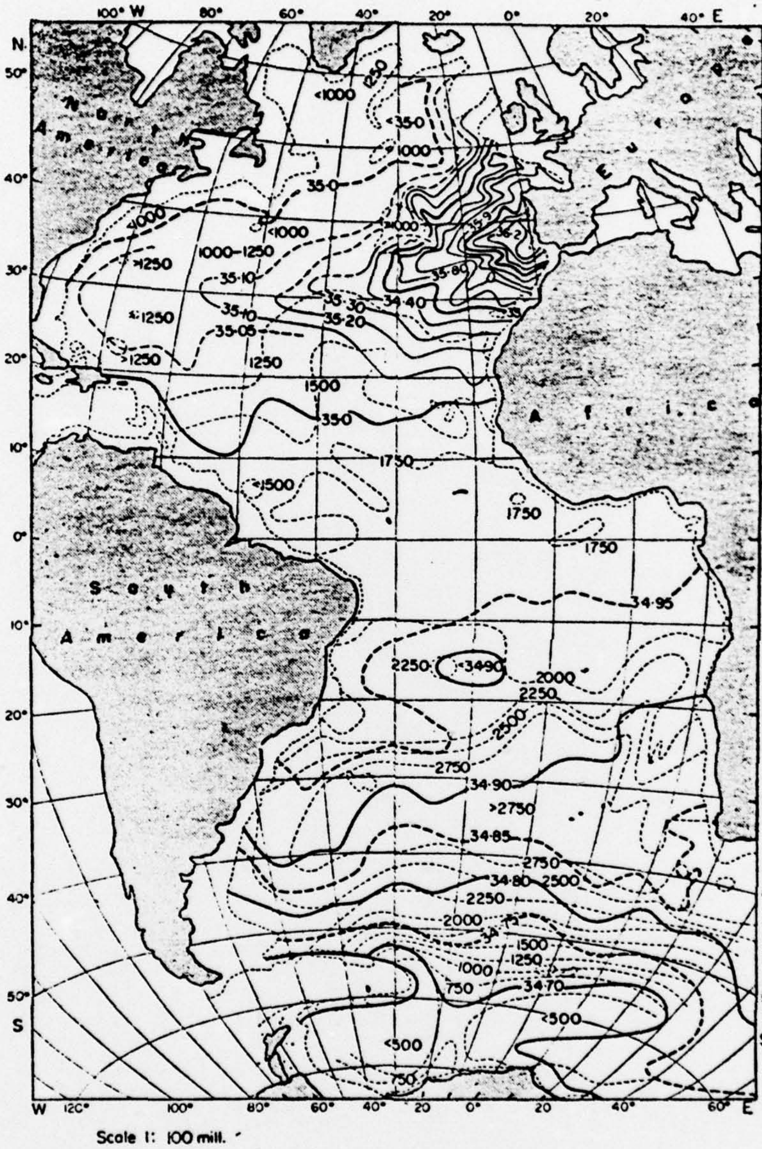


Fig. 8 - Spreading of Upper Deep Water in the North Atlantic as characterized by salinity in the core of the salinity maximum. Dashed lines indicate depth (m) of the core layer (from Defant, 1961).

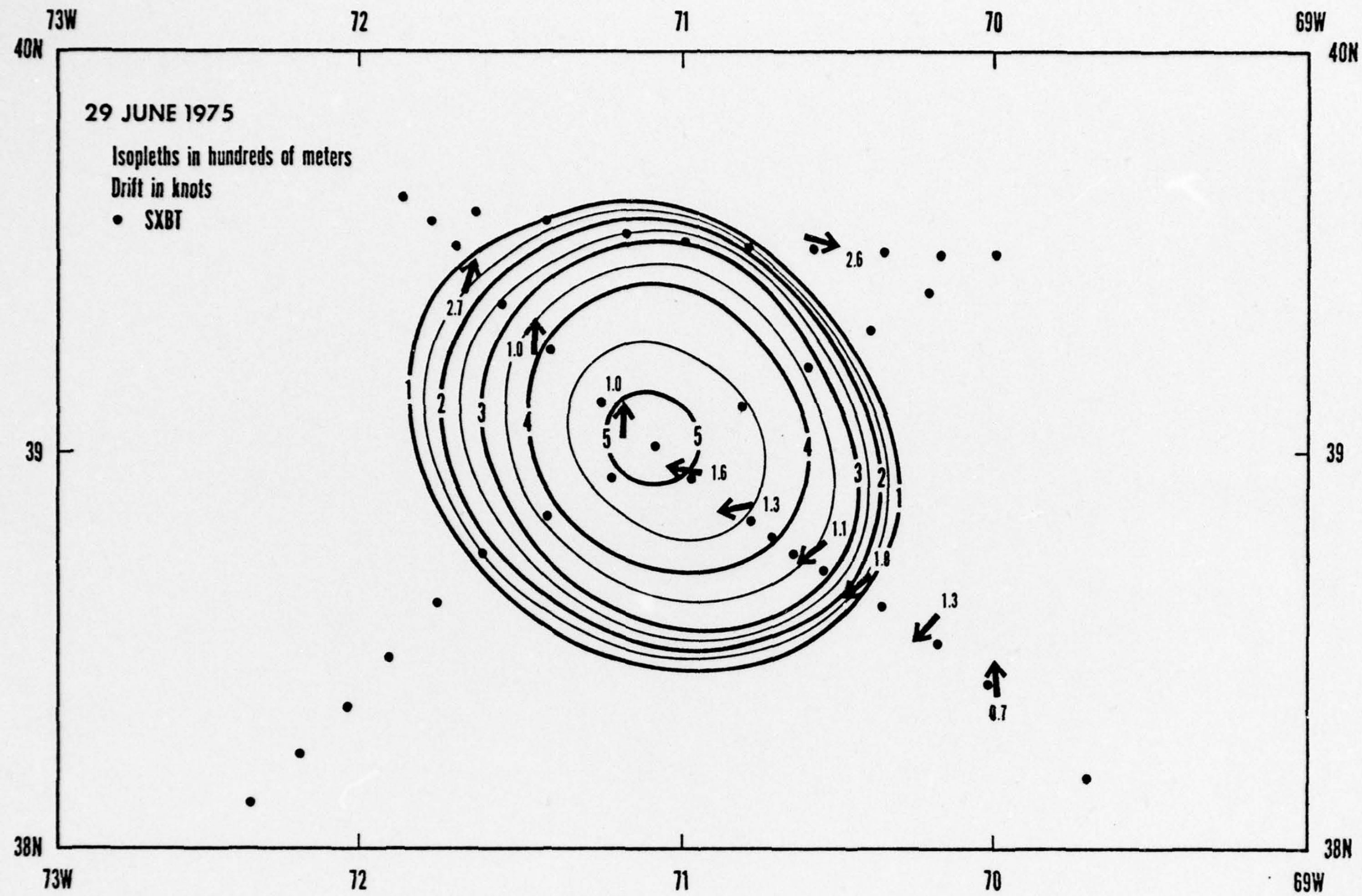
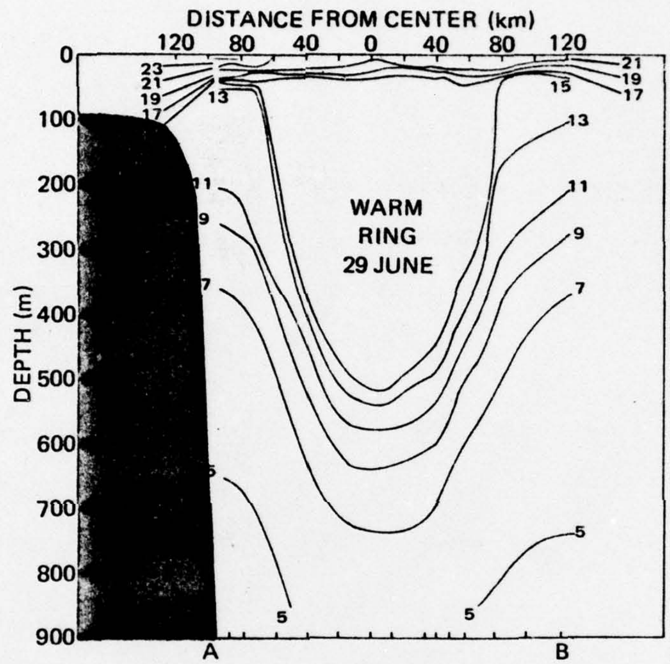


Fig. 9a - 15°C depth (10^2 m) in the warm ring, 29 June 1975. SXBT positions and surface currents (knots) as determined from ship drift are indicated.



39°38'N 71°54'W	38°25'N 70°01'W

Fig. 9b - Temperature section through the warm ring. SXBT positions are shown along bottom. Darkened area is continental slope.

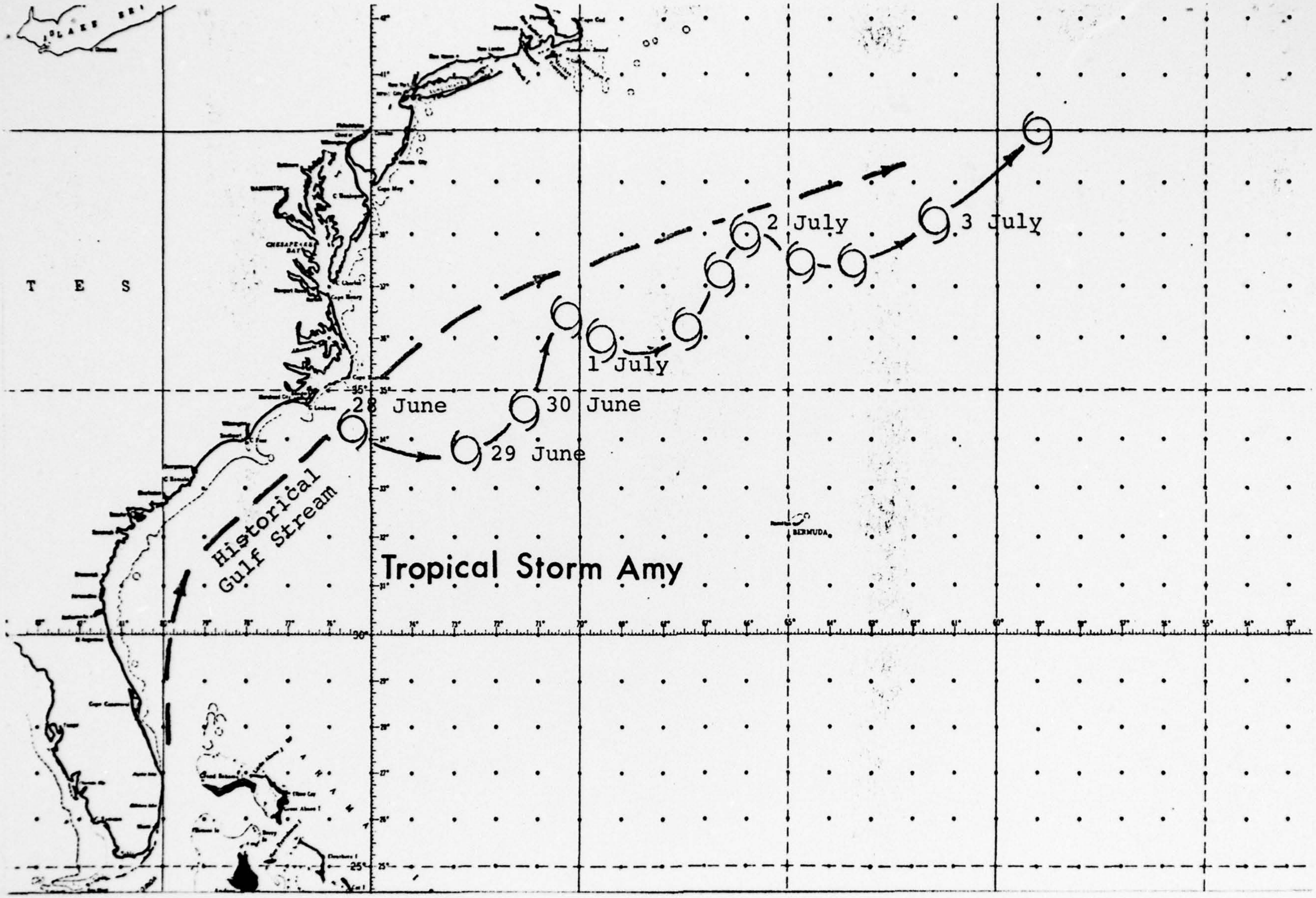
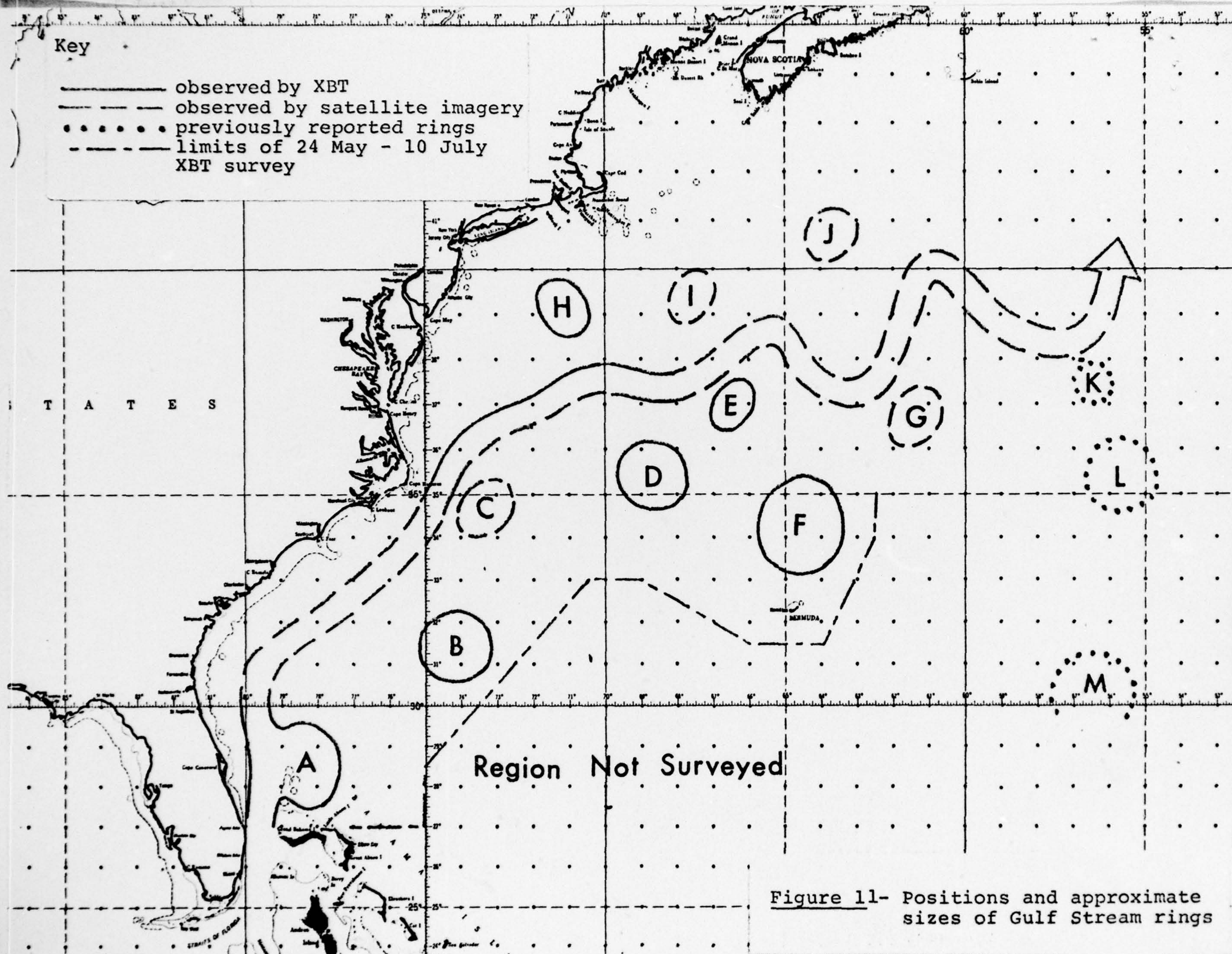


Fig. 10 - Movement of Tropical Storm Amy between 28 June and 3 July 1975. Maximum sustained wind speeds were 60 knots near the center with gusts to 80 knots.



<u>Figure 11</u>- Positions and approximate sizes of Gulf Stream rings

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